Challenges in Robotic and Robot-Assistive Activities on the Moon and Mars

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Abstract—**Operating robots on other planets offers challenges to the mission operations teams due to time-delay of signals over long distances, harsh environments, and the difficulty of fixing things. Standard teleoperations tools must be adapted and extended to deal with these challenges while providing an optimal balance between safety and productivity. Additional autonomy is necessary onboard the robot in order to accomplish many tasks and the tools must be capable of interacting with and commanding such autonomy.** **Keywords - robotics, telerobotics, teleoperations, autonomy.**

I. Introduction

The National Aeronautics and Space Administration (NASA) is currently tasked with expanding the human presence into the Solar System. Beginning with the Moon and continuing with Mars, astronauts will begin to build and occupy semi-permanent and permanent stations on other planetary surfaces. In order to safely and efficiently construct such stations, robotic assistance will be necessary to avoid astronaut exposure to radiation and other dangerous environmental effects. Robots will be used to prepare sites, build structures, haul cargo, and provide other support capabilities.

The Jet Propulsion Laboratory, California Institute of Technology, is currently developing and testing a robot for providing such capabilities. The ATHLETE (All-Terrain, Hex-Limbed, Extra-Terrestrial Explorer) robot is a six-limbed robot able to carry cargo and habitats as well as utilize tools for manipulation, construction, digging, augering, and other activities. Three of the ATHLETE robots have been built and are undergoing a series of field trials where their capabilities are explored. Of particular importance are the operational mechanisms whereby the goals of the operators are conveyed to the robots and translated into actions.

Much work has been done in the field of telerobotics. One of the findings is that the information required by the operator is strongly dependent on the capabilities and limitations of the robot. Thus, there is no generic solution to the problem of operating a robot. Instead, a variety of techniques must be adapted and combined to provide the optimal paradigm for the robot being controlled. For example, a robot on the Moon may be teleoperated from Earth with only 5-20 seconds of time-delay. This would be typical during the early construction phases of a Lunar station. On Mars, however, the time-delay of 3-20 minutes would preclude such teleoperations and instead require more autonomy in the robot or local operators either in orbit or on the surface. An additional wrinkle is in robot-assistive operations where humans and robots work side-by-side and each must adapt to the actions of the other.

Thus, the challenges faced in operating a robot such as ATHLETE derive from its unique capabilities and mission. It is very flexible, with six degrees of freedom for each of six limbs, additional degrees with various tools, the ability to roll over smooth terrain for efficient traversals along with the ability to walk over very rough terrain and climb steep slopes, and the ability to carry cargo in various shapes and sizes. Its mission is not to explore, as is the case for MER, but to assist in the form of building and carrying. This is a very complex and capable robot that presents unique challenges in just controlling so many degrees of freedom. The goal of any tools used to operate such a robot is to present the state of the robot in the most intuitive, information-efficient manner while translating operator goals into safe, efficient robot actions. The realization of this goal must transition from presenting low-level information, such as joint angles and torques needed during field tests, to higher-level information, such as goals needed during flight operations, as the level of autonomy increases in the onboard systems. It is a challenge to develop tools and paradigms that work across such a broad spectrum of needs and uses. An important challenge in presenting robot state to the operator is the use of terrain models for analyzing and visualizing traversability issues such as smoothness for rolling or footfall placement during walking. Existing systems do one or the other and this combination of both is a new capability.

These challenges will continue to face NASA for many years to come as specific exploration activities proceed, Lunar and Martian landings of robots and astronauts occur, and humans explore more of our Solar System.

II. ATHLETE Capabilities

The ATHLETE robot is a six-limbed robot with each limb

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attached at the corner of a hexagonal frame (see figure 1). Each limb terminates in a wheel to allow traversing over smooth terrain with low energy consumption. Each limb also has six degrees of freedom allowing the robot to lock the wheels and walk or climb. In addition, each limb can have a tool attached and use the flexibility of the limb to position the tool anywhere within a large work volume. Figure 2 shows the three current tools available for ATHLETE, a gripper, an auger, and a small scoop. ATHLETE can carry large payloads, up to 300 kilograms for the test robots on Earth, on top of the hex frame or slung beneath. Smaller loads can be picked up by a single limb, or two cooperating limbs, and carried. Figure 3 shows ATHLETE carrying a payload on top of the frame and by a single limb. Sections of a payload can be picked up and placed on top of the hex frame, i.e. ATHLETE can load and unload itself.

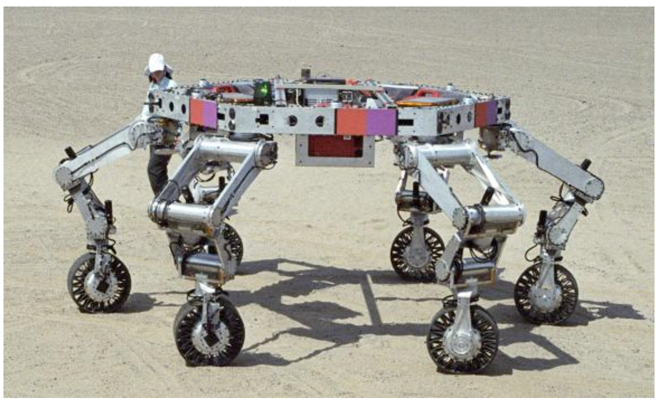

Figure 1 - The ATHLETE Robot

During the first field tests, the ATHLETE robots were operated from a simple command-line interface. A spotter with a walkie-talkie would essentially issue commands and the operator would enter those commands on the console and send them to the robot. The spotter was responsible for monitoring the robot state, specifying commands to adjust

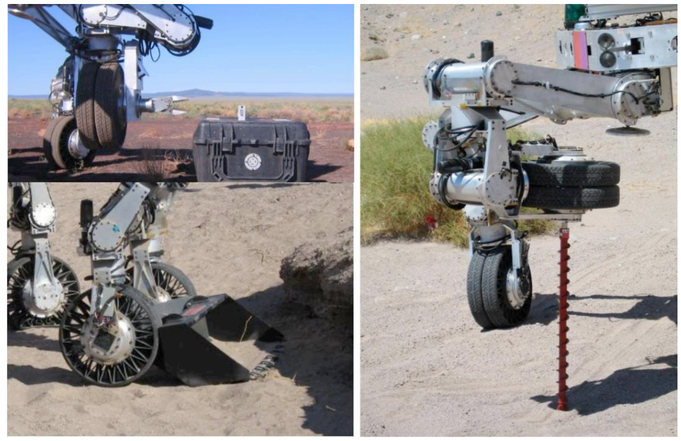

Figure 2 - ATHLETE's Tools

the state, such as leveling the body, and stopping the robot if an unintended action occurred. Telemetry from the robot to the operator was limited. A particular problem was that there were no tools aiding the commanding process to display the parameters needed for a command or to verify units or value ranges. Thus, only experts in the continually changing command dictionary could be operators.

As the field tests have progressed, additional capabilities and tools have been added to the command suite including tools adapted from use on the Mars Exploration Rover (MER) missions and new tools developed specifically for this robot. These tools provide three-dimensional, stereo views of the local terrain, produce 3D terrain models for immersive displays, animate models of the robot to display current state, display telemetry in easy to understand formats, maintain commands in a structured form that is easy to edit, and make it simple to send commands to the robot.

A. Teleoperations

As mentioned above, the original paradigm was a spotter specifying commands and an operator issuing the commands to the robot. Additional modes have been demonstrated and

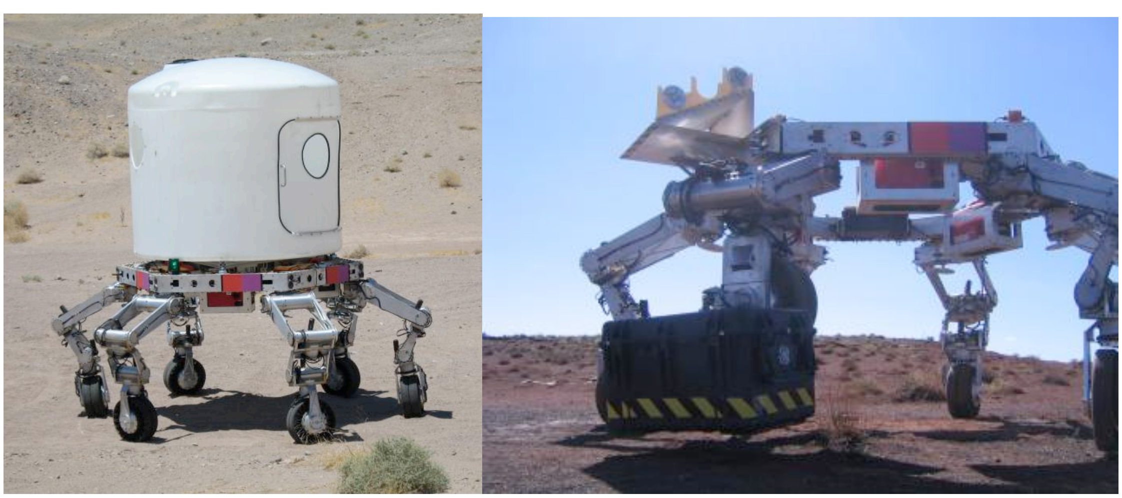

Figure 3 - ATHLETE Carrying Payload and Small Cargo

others are under development. Use of the immersive displays to provide feedback to an operator with no spotter input has been demonstrated for some tasks. In particular, immersive displays can convey enormous amounts of information to an operator that is very difficult to assimilate in other modes. Commanding with time-delay has been demonstrated yet presents ongoing challenges. Collaborative methods to enhance commanding performance under time-delay constraints are just being utilized and issues identified.

1) Immersion

The first demonstration of an unassisted operator performing a task was in lifting a small payload using the gripper on a limb. The operator issued commands to drive a short distance to approach the payload, raise the limb off the ground, and turn the gripper tool to address the lift ring on the object. Then, utilizing the stereo imagery from the tool cameras mounted on the legs above the tools, adjusted the position of the tool and moved the gripper into position. The gripper was activated and the payload lifted off the ground before driving away from the location. This activity was a milestone despite its apparent simplicity. The addition of several more stereo cameras on the robot have made this task much simpler. However, this paradigm is highly interactive and is not feasible with significant time-delay.

Figure 4 is an image of the ATHLETE operator's cockpit. The top three monitors are autostereoscopic and each displays the left and right images from a pair of cameras on the robot. For driving, these would typically display the images from the cameras on the side facing the main drive direction, as well as the images from the sides immediately to the right and left. Because the displays are autostereoscopic, the user can see depth without the use of special glasses and gauge the terrain ahead. The monitors can also display imagery from the cameras slung beneath the frame to visualize the terrain beneath the robot or from the tool cameras mounted on the ankles above the tools. This level of partial immersion is very useful in that it allows for rapid transitions between the immersive sensation and viewing information, such as numeric values and text displays, that do not benefit from and are not conducive to immersive displays.

The lower right monitor displays a three-dimensional model of the robot and its environment. The environment consists of a terrain model (see below for a brief description of the terrain modelling process), certain components such as boxes or other objects to manipulate, and factors such as sun position to evaluate shadowing. Again, this three-dimensional display, with operator interaction with the camera viewpoint, provides a useful level of immersion while being able to easily transition to other types of displays. The middle monitor displays the main tool used for generating commands and for inputting and verifying the command arguments. The left monitor displays telemetry in a variety of formats for reference.

2) Time-Delay

The addition of time-delay in the control loop for the robot adds significant complexity. For operations on MARS, as in the MER missions, the approach used is to build and rehearse complete command sequences on the ground and uplink them to the robots on a daily basis. The robots then go about their business autonomously. For Lunar missions, the several seconds of time-delay would not require such an approach but would not allow free interaction with the robot. In this case, the approach is to rehearse some actions prior to commanding and to simulate some actions as they are occurring. Rehearsal is made possible by producing three-dimensional terrain models from the stereo imagery captured by the onboard cameras[1]. At any time, the operator may command the acquisition of a set of stereo images and the production of a terrain model, a process that takes about one minute. Then the operator uses an inverse kinematics mode in the three-dimensional viewing tool to manipulate a limb and position a tool to perform a task. The actions can be rehearsed in a few seconds and then sent to the robot with the reasonable expectation that the commanded behavior will occur. Walking can be performed the same way, with terrain models acquired and analyzed for safe footfall locations and appropriate commanding generated, rehearsed, and sent.

Figure 4 – The ATHLETE Cockpit

Driving, however, is much more problematic. The ATHLETE robots are capable of driving over smooth terrain at up to 10 km/hour. At that rate, the robot will traverse out of the known terrain in a few seconds. Stopping to acquire new terrain models would slow the traverse dramatically. In order to support driving, a robot simulator has been incorporated into the command tools. This simulator produces the same telemetry that the real robot produces. The real robot streams imagery to the command displays as fast as possible and the operator issues driving commands. These commands are sent to the simulator and the actual robot at the same time. The simulator begins simulating the commands immediately and the resulting telemetry is displayed in the form of an animated robot model. This is a predictive display of the expected robot behavior. An optional second copy of the telemetry may be similarly displayed, delayed by one-half of the time-delay, to illustrate the expected current state of the robot. Then the actual telemetry from the robot, delayed by the full time-delay, is displayed to show last known state. Validity of the simulation is highly dependent on knowledge of the terrain so this methodology is only truly effective in very uniform areas or during slow traverses in which additional terrain models can be acquired prior to the previous terrain model becoming irrelevant.

3) Planner/Executor

Another operational approach to improving effectiveness in the presence of time-delay is the Planner/Executor paradigm. In this approach, an operator, the Planner, is responsible for a more strategic view of the tactical planning process. The Planner produces command sequences, simulates them, and adjusts them, until the desired behavior is occurring. Then, instead of sending the commands to the robot, they are passed to the Executor who is responsible for shepherding the commands to the robot, verifying behavior, clearing errors, and producing additional commanding for situations that were not previously known, such as obstacles encountered. At certain points in the process, such as reaching an object to be picked up, a state synchronization occurs in which the Planner receives up-to-date telemetry and terrain models in order to begin planning interactions with the object. This shared responsibility may allow more optimal use of the robot. However, this paradigm is currently being explored and the division of responsibility to achieve that optimum is not yet clear.

B. Autonomous Capabilities

One important technique for improving performance in the presence of time-delay is to make the robot more autonomous. Several techniques, including Visual Terrain Tracking, Hazard Avoidance, and Auto-Placement, have been, or are being, tested on the MER robots on Mars. These capabilities can be utilized by the ATHLETE robots to simplify the commanding and produce better operational results.

1) Hazard Avoidance

Hazard Avoidance utilizes stereo imagery of the terrain in order to identify hazards in the planned drive direction and to look for safer alternatives. This capability has been on the MER robots since landing[2,3,4] and utilization of the techniques on ATHLETE would make driving on long traverses much safer in the presence of significant time-delay. In this mode, traversing would be commanded using potentially widely separated waypoints with the robot choosing the route between.

The hazard avoidance process captures stereo imagery at regular intervals as the robot traverses the terrain. The stereo imagery is processed to generate three-dimensional models of the nearby terrain and these models are analyzed for hazards based on the robot's capabilities. In particular, the height of local features such as rocks and the slope of larger features are used to determine traversability and hazard level of the terrain. A hazard map is kept updated covering the local region and is scrolled as the robot moves to keep it in the center of the map. Thus, hazards identified in the drive direction will move with the map to provide information on regions not currently visible. Specifically, hazards directly underneath the robot are only recognized if they were previously identified ahead of the robot and kept in the map as the robot drove over them.

2) Visual Terrain Tracking

Visual Terrain Tracking (also known as Visual Target Tracking [5,6,7]) is a newer technique currently undergoing testing on the Martian surface on MER. This technology uses imagery to track a designated terrain feature as the robot moves in order to make an accurate approach to the feature. For ATHLETE, the feature could be a cargo container or tool. Allowing autonomous approaches to a cargo container that could be expected to be accurate would eliminate many adjustments requiring human in the loop interactions over high-latency links. A similar feature is already present in the ATHLETE flight software. This feature tracks the colored docking markers, seen on the side of the robot in figure 1, of other robots and provides telemetry on the distance, direction, and orientation of the specified marker. This information can be used to command a robot to approach and dock with another robot. Docking allows the robots to provide larger carrying capacity or bring modules together to build larger facilities.

3) Auto-Placement

Auto-Placement is another new technique being tested on Mars by MER[7]. Auto-placement allows the robot to select an appropriate location on a specified rock and use the robotic arm to place an instrument on the self-selected location. The robot selects locations that are reachable and avoid collisions between the arm and other parts of the rock. Such a technology would be used by ATHLETE to identify pickup points on cargo containers or attach points for tools and allow a limb to perform operations autonomously.

The combination of the above features would allow an operator to issue a command such as "Go pick up THAT

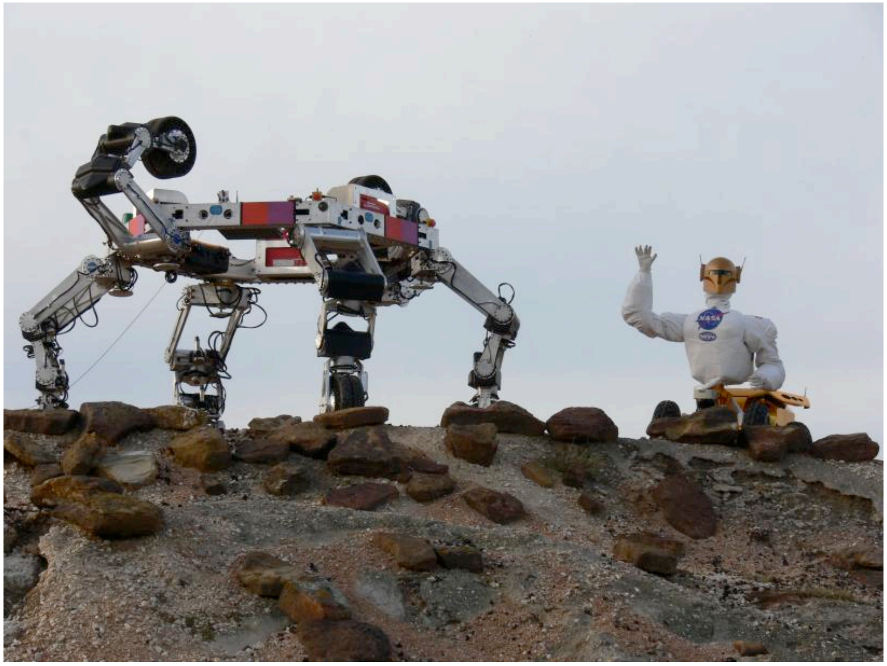
Figure 5 - ATHLETE and Robonaut

container." The action would occur safely, if possible, and not require human interaction.

III. Robot-Assistive Operations

Once astronauts arrive on the Moon or Mars, the robots will be expected to work with the astronauts on additional tasks. In many cases, the robots and astronauts will work collaboratively on robot-assistive tasks with the robot providing strength and the astronaut providing dexterity and control. For example, the robot could hold a truss while the astronaut attaches it or the robot could drive an auger to anchor a device positioned by the astronaut. Some of these operations could be performed by a dexterous robot, such as Robonaut, seen with ATHLETE in figure 5, but direct astronaut-robot interactions are very likely and must be safe and effective.

A. Control

The control paradigm for this interaction suddenly reverts back to the walkie-talkie mode described above. The astronaut issues commands and the robot obeys them. This can be accomplished via a second astronaut operating the robot from a local facility or by adding the ability to perform voice and/or gesture recognition onboard the robot.

1) Voice Recognition

Voice recognition is slowly becoming a usable tool on current desktop computers. Adding such a capability to robots has been demonstrated by researchers[8] and hobbyists[9] and is likely to be incorporated in NASA robots in the not too distant future. In order to avoid incorrect identification of commands, a simple command language is likely to be used and the recognition engines tuned to the specific astronauts to work with them. Even simple commands such as "Move down 5 centimeters" are subject to problems as the command could mean lower the body 5cm or lower the current tool 5cm.

2) Gesture Recognition

Gesture recognition is another capability that is being explored and some simple gesture recognition systems have been demonstrated [10,11]. Arm gestures could be used to direct the placement of cargo to unmarked areas, similar to directing a truck backing into a tight spot. Finger gestures could be used to specify small motions of a limb for more precise placement of a tool. These would be limited by the flexibility, range of motion, and the presence or lack of distinguishing features on astronaut suits. Adding markers on fingertips, for example, could enhance the ability of the robot to distinguish the relative finger positions and perform the correct action.

IV. Conclusion

Operating the ATHLETE robots on the Moon or Mars provides challenges to current teleoperations technology. Many techniques previously developed will be applicable and some new ones will need to be invented. The use of robots for construction, maintenance, and operation of stations on other planets, in conjunction with astronauts, will continue to challenge for the foreseeable future. The techniques and concepts presented here are only a subset of those being considered for operations. Only the continued exploration of such techniques will allow us to meet the challenges of human presence throughout the Solar System.

V. Acknowledgment

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